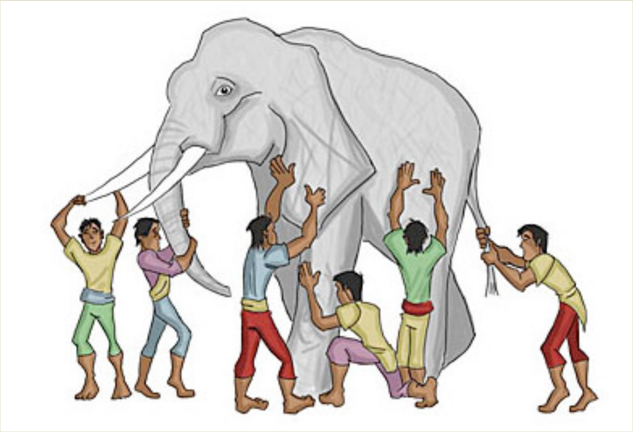


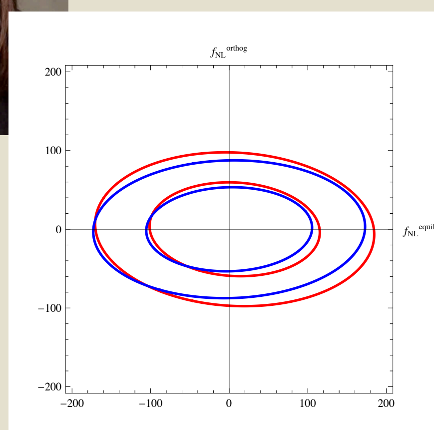
Discerning dark energy's character

Rachel Bean
Cornell University

In collaboration with:
Eva-Marie Mueller (Cornell)
Istvan Laszlo (Cornell)
Sarah Bridle (UCL)
Donnacha Kirk (UCL)
Scott Watson (Syracuse)

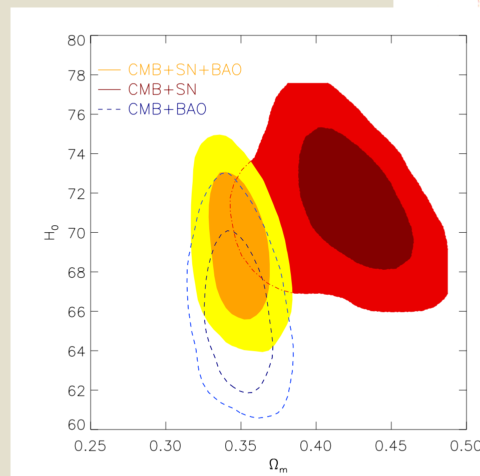
Poster sessions

Joyce Byun



Primordial non-Gaussian shape recognition

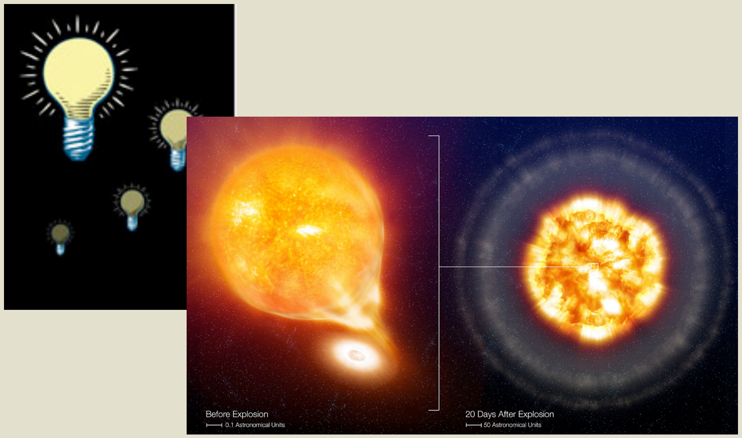
Eva Marie Mueller



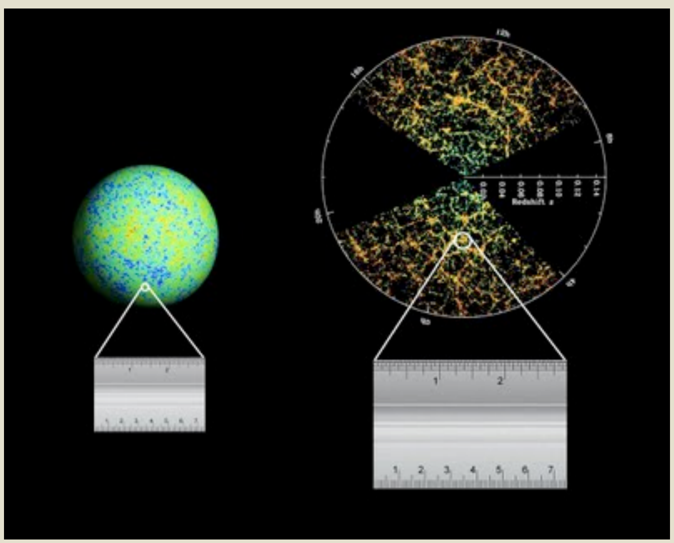
Cosmological constraints on the effective field theory and cosmic acceleration

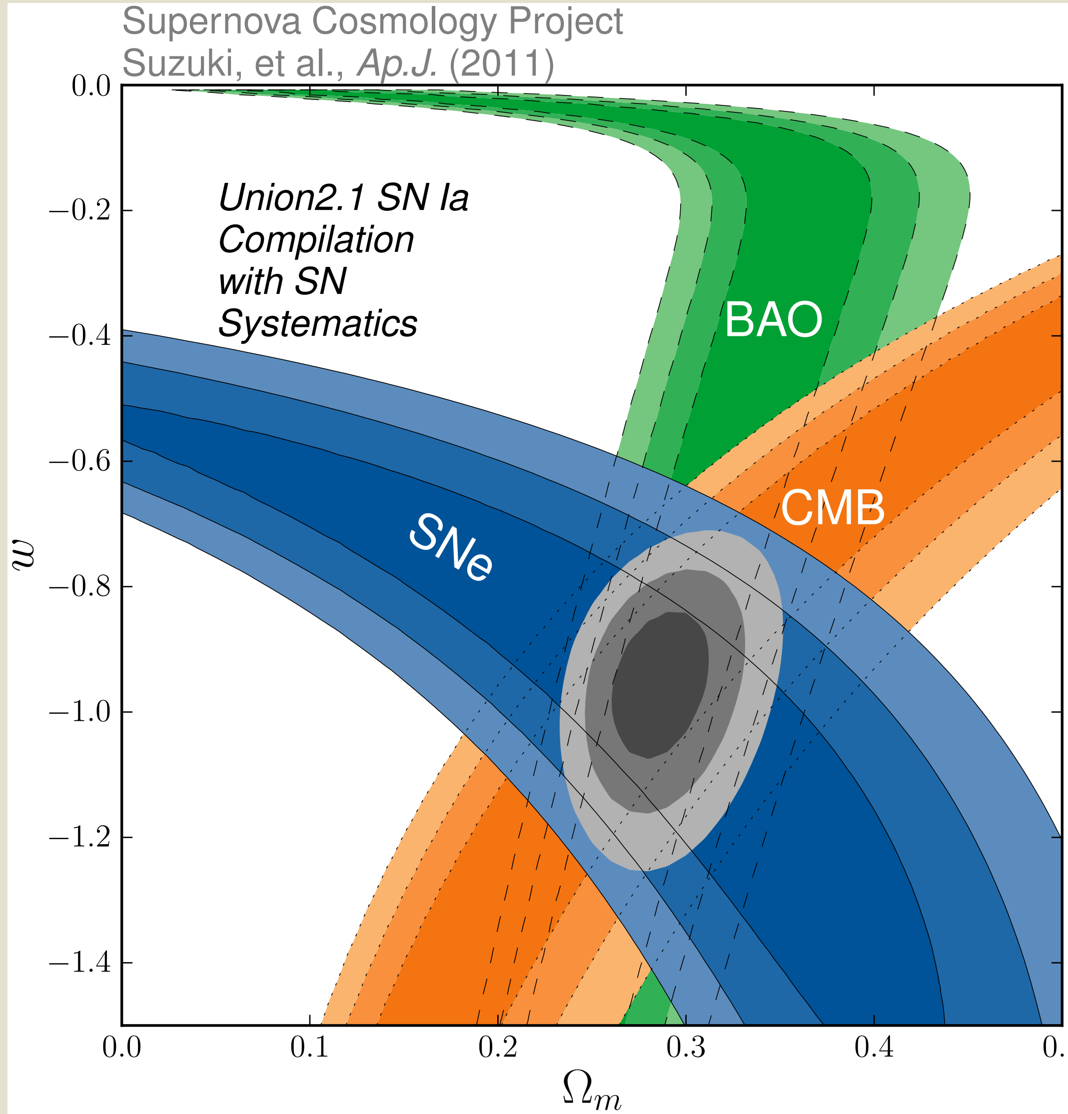
Geometric complementarity gives powerful evidence for dark energy's existence

Standard candles

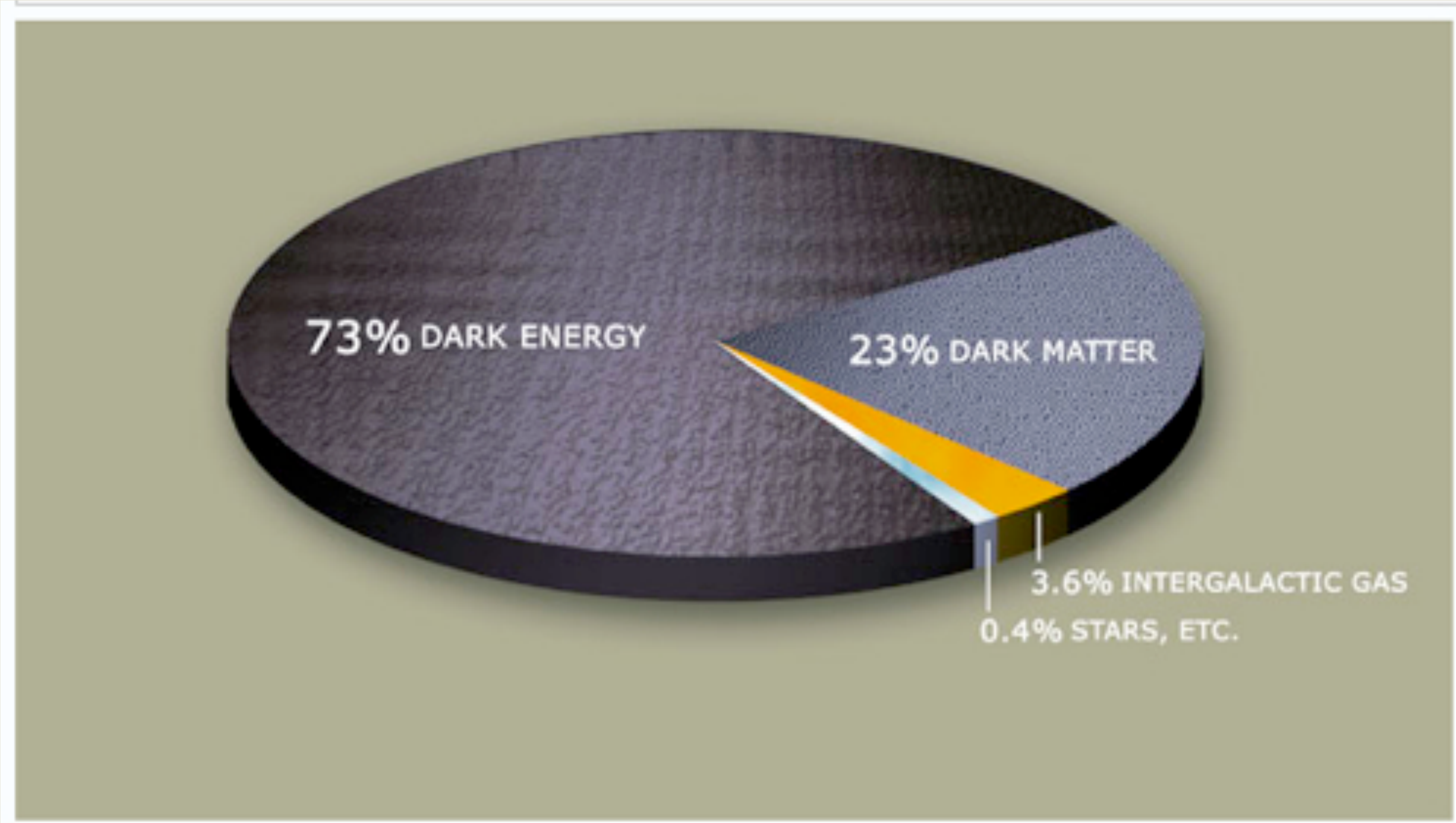


Standard rulers





The concordance camembert

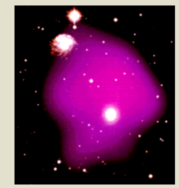


Understanding cosmic acceleration

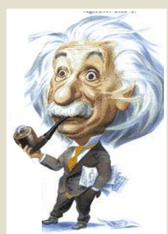
Cosmic acceleration = a modification of Einstein's equations

Deviations from GR?

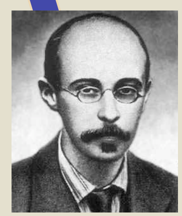
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$



New matter? interactions?



Λ?



Inhomogeneous universe?

Broad aim =Phenomenology
Distinguish which sector: new gravity, new matter or Λ?

Ambitious aim = Theoretical model
Learn something more about the underlying theory?

Ways to modify gravity?

- Scalar tensor gravity = simple models we can model effects for

GR
$$S = \int d^4x\sqrt{-g}\frac{1}{16\pi G}R$$

f(R) gravity
$$S = \int d^4x\sqrt{-g}\frac{1}{16\pi G}\left(R + f_2(R)\right)$$

Scalar tensor gravity
$$S = \int d^4x\sqrt{-g}\frac{1}{16\pi G}f_1(\phi)R$$

Higher dimensional gravity e.g. DGP
$$S = \int d^5x\sqrt{-g^{(5)}}\frac{1}{16\pi G^{(5)}}R^{(5)}$$

- Active area of research, many different options, no solutions, yet
- Common theme: A scalar degree of freedom

Alternative explanations to expansion history

- Alter Friedmann and acceleration equations at late times

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + 3P_m) + stuff$$

or

$$stuff + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + 3P_m)$$?

e.g. f(R) gravity

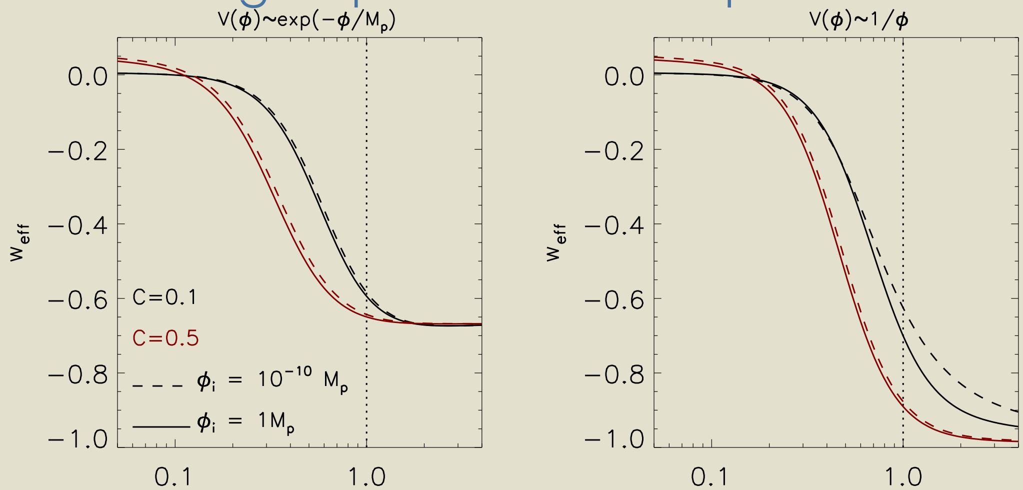
$$-H^2 f_R + \frac{a^2}{6} f + \frac{3}{2} H \dot{f}_R + \frac{1}{2}\ddot{f}_R + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

e.g. DGP gravity

$$-\frac{\dot{H}}{r_c} + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

Palatable and unpalatable attraction…

- Attractor solutions give predictions independent of initial conditions,



RB, Flanagan, Laszlo, Trodden 2008

  - for better or worse e.g. f(R) Amendola et al 2007

- Can evade (unpalatable) attractors, by retrofitting ΛCDM background, but at the high price of more fine-tuning
  - e.g. f(R) Hu and Sawicki 2007

$$f(R) \;=\; -m^2\frac{c_1(R/m^2)^n}{c_2(R/m^2)^n+1}\,,$$

Can we tie data a step closer to theory?

- What observational properties might the most general action predict?

$$S = \int d^4x\sqrt{-g}\left\{\frac{M_p^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi)\right.$$

Canonical scalar field

$$+f_{quartic}(\phi)(\nabla\phi)^4$$

Quartic kinetic

$$+f_{curv}(\phi)G^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi$$

Coupling to curvature

$$\left.+f_{GB}(\phi)\left(R^2 - 4R^{\mu\nu}R_{\mu\nu} + R_{\mu\nu\sigma\rho}R^{\mu\nu\sigma\rho}\right)\right\}$$

Gauss-Bonnet (GB) term

$$+S_{\rm m}\left[e^{\alpha(\phi)}g_{\mu\nu}\left(1+f_{kin}(\phi)(\nabla\phi)^2\right), \psi_{\rm m}\right]$$

Non-minimally coupling to matter

Park, Watson, Zurek 2011
Bloomfield & Flanagan 2012
Bean, Mueller, Watson in prep

Attractor behaviors

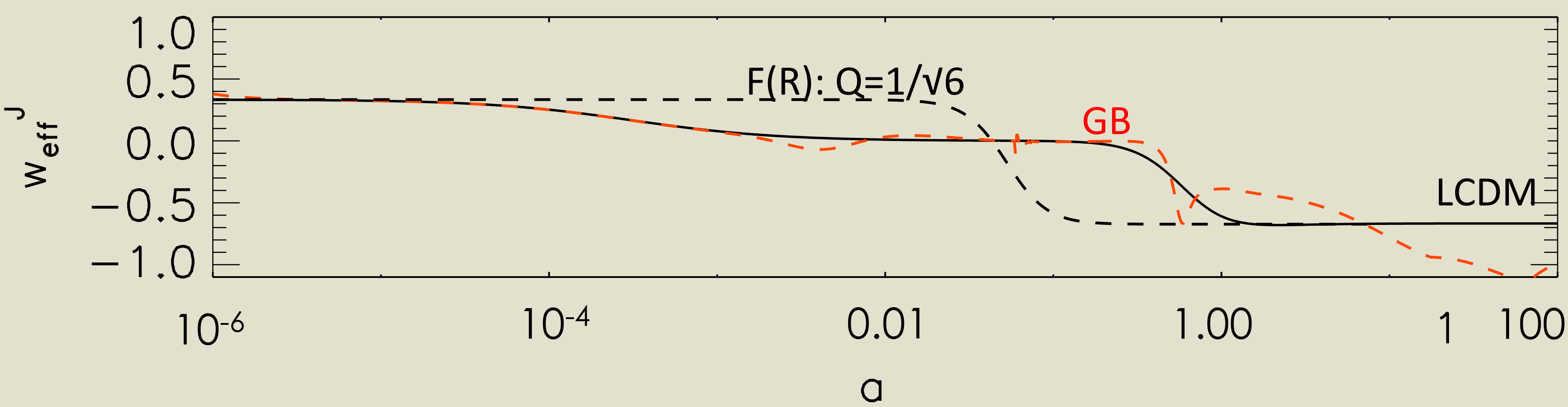
- Simple forms for couplings/interactions yield a small set of predictions

Attractor	Ω_ϕ	w_ϕ	w_E	w_J
MAT$-\lambda$	$\frac{3(1+w_m)}{\lambda^2}$	w_m	w_m	$\frac{w_m+\sqrt{6}Qx/3}{1-\sqrt{6}Qx}$
MAT $-$ Q	$\frac{2Q^2}{3}$	1	$\frac{2Q^2}{3}$	$\frac{4Q^2}{3(1-2Q^2)}$
ACC$-\lambda$	1	$-1+\frac{\lambda^2}{3}$	$-1+\frac{\lambda^2}{3}$	$-1+\frac{\lambda^2-2Q\lambda}{3(1-Q\lambda)}$
ACC $-$ GB	1	-1	-1	-1

$$V = V_0 \exp\left(-\lambda\frac{\phi}{M_p}\right)$$

$$e^\alpha = \exp\left(-2Q\frac{\phi}{M_p}\right)$$

$$f_{GB} = F_0 \exp\left(-\mu\frac{\phi}{M_p}\right)$$

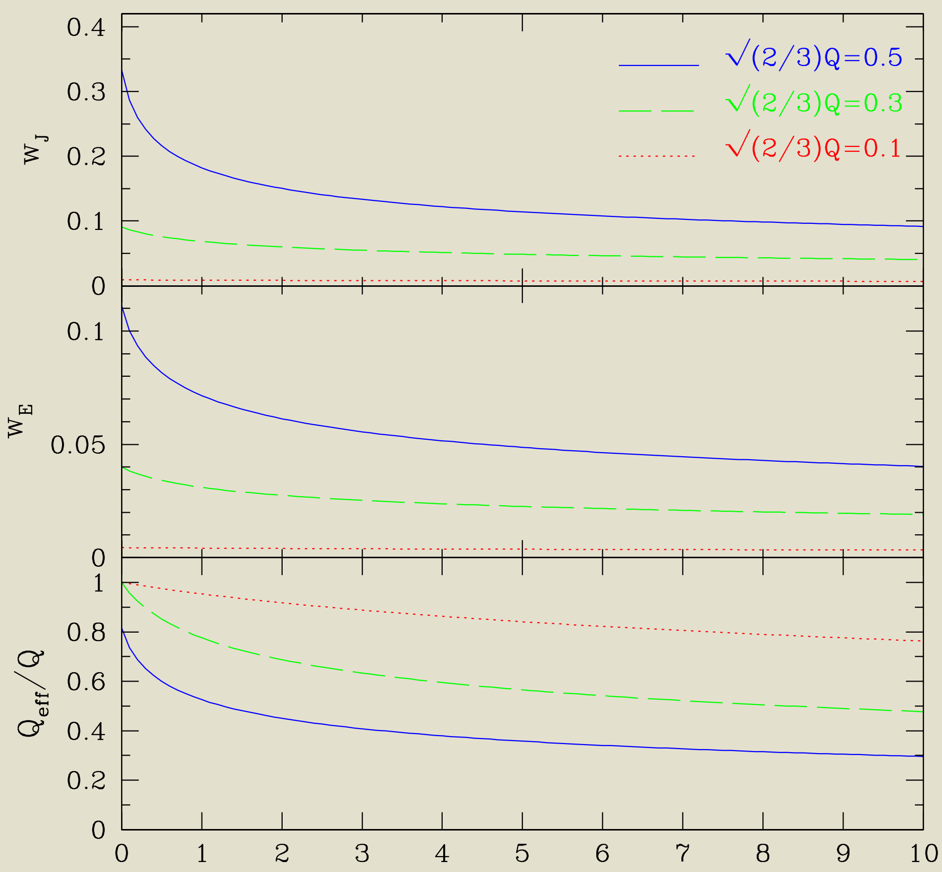


Rachel Bean: CMU August 2012

Bean, Mueller, Watson in prep

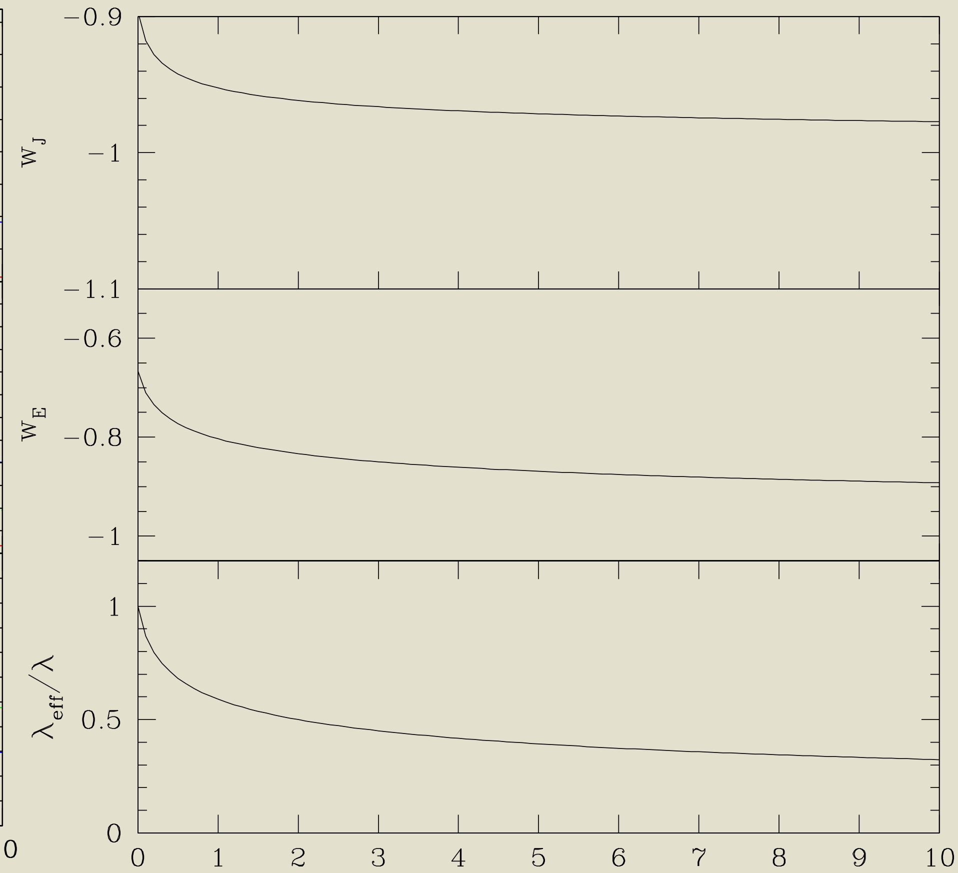
Quartic and curvature interactions have cosmologically interesting effects

Matter dominated era



Increasing quartic term →

Late time accelerating era

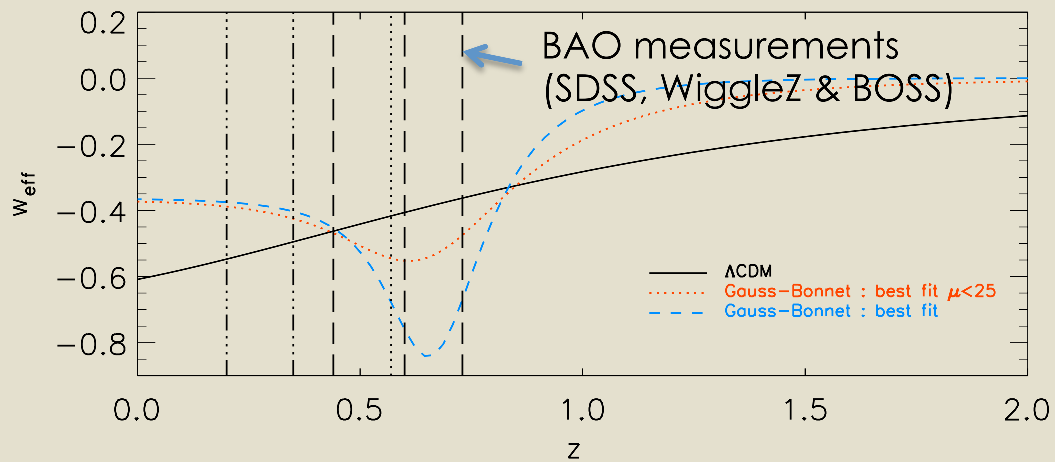


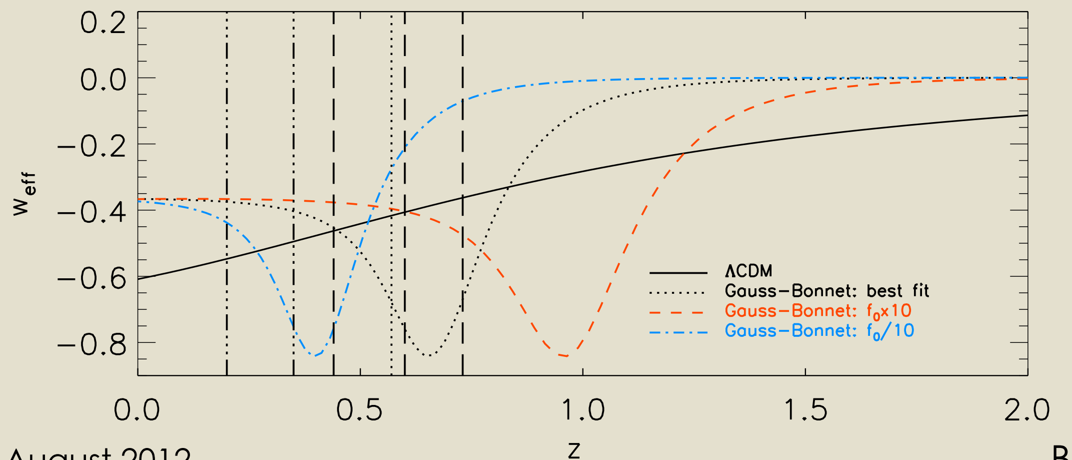
Increasing quartic term →

Bean, Mueller, Watson in prep

The power of multi-epoch measurements

- BAO and SN data give multiple tests of cosmic dynamics

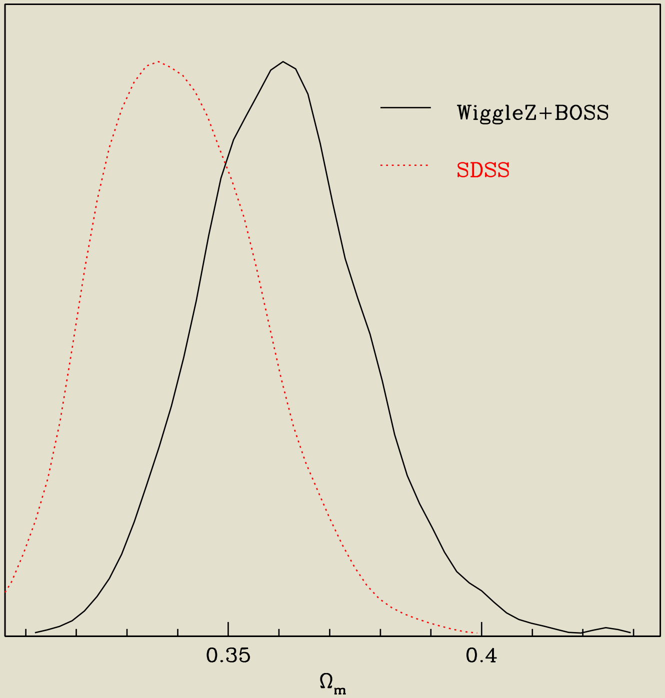


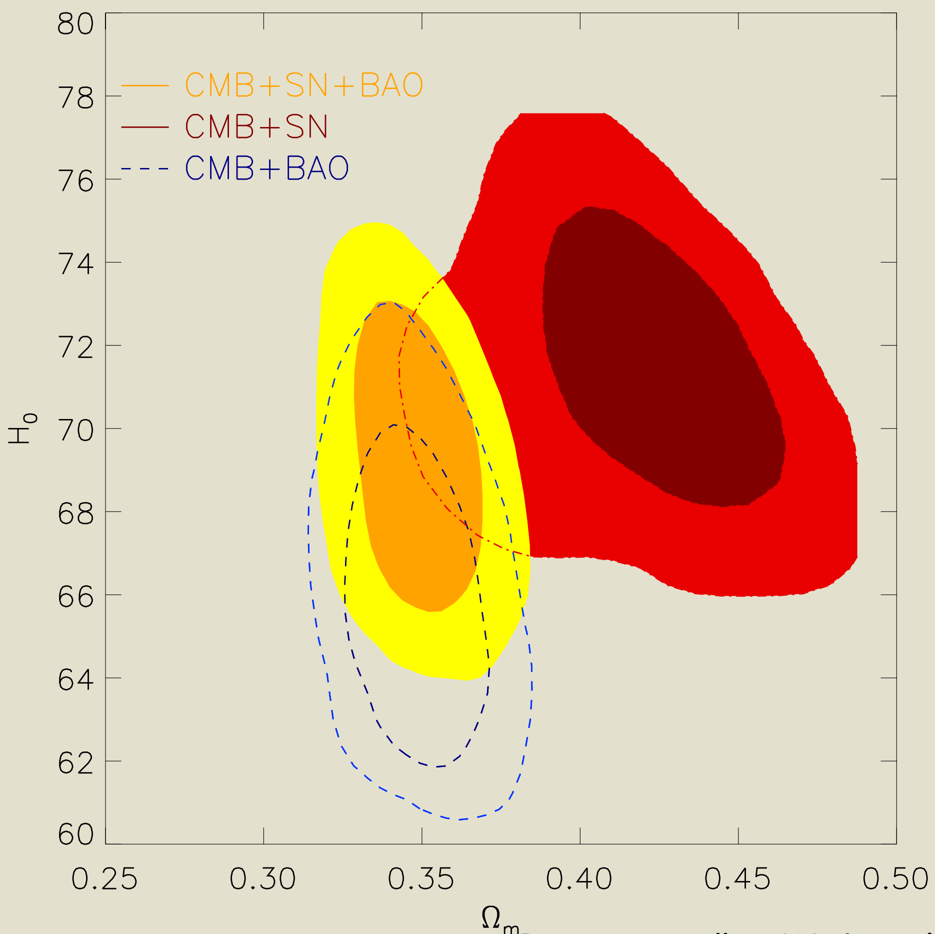


Bean, Mueller, Watson in prep

The power of multi-epoch measurements

- In combination, rule out Gauss-Bonnet term: $\Delta\chi^2$(GB-LCDM)=+17

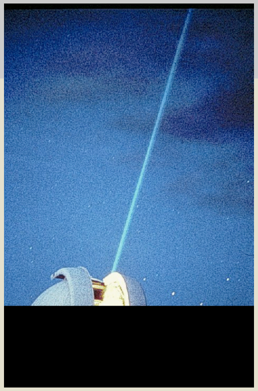




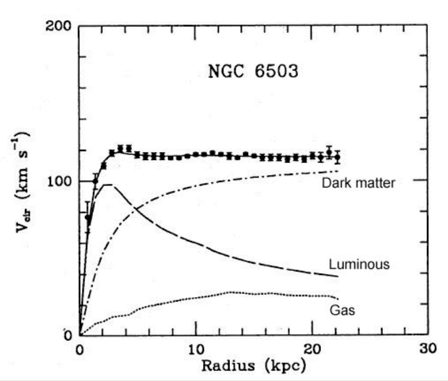
Bean, Mueller, Watson in prep

There are always benefits to asking more questions…

Weak field tests of gravity

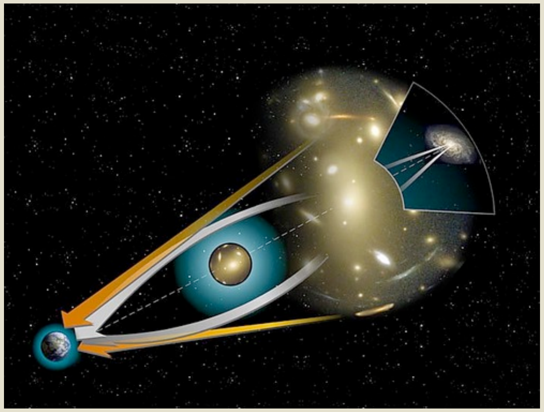


- Terrestrial and Solar System
  - Lab tests on mm scales
  - Lunar and planetary ranging



- Galactic
  - Galactic rotation curves and velocity dispersions
  - Satellite galaxy dynamics

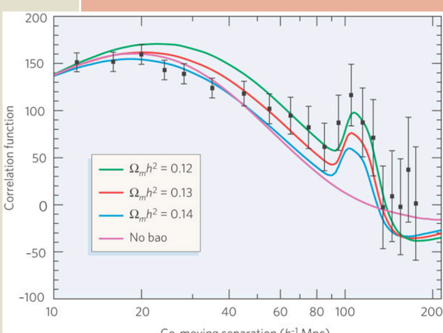
- Intergalactic and Cluster
  - Galaxy lensing and peculiar motions
  - Cluster dynamical, X-ray & lensing mass estimates

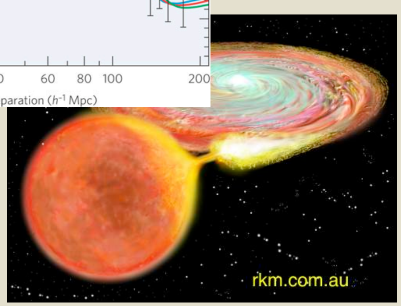


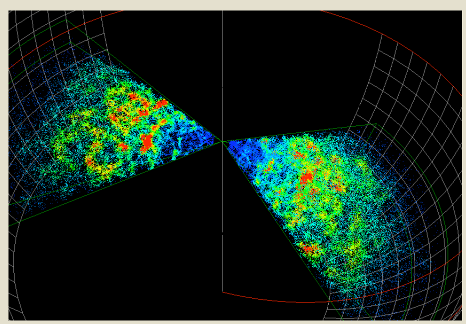
- Cosmological
  - Early times: BBN, CMB correlations
  - Late times: Large scale structure

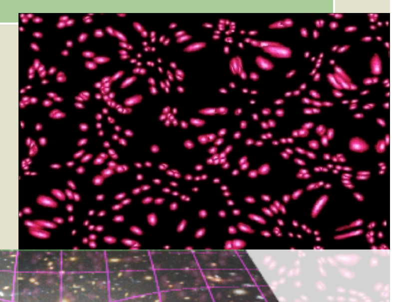
Three groups of extra galactic observations for testing gravity

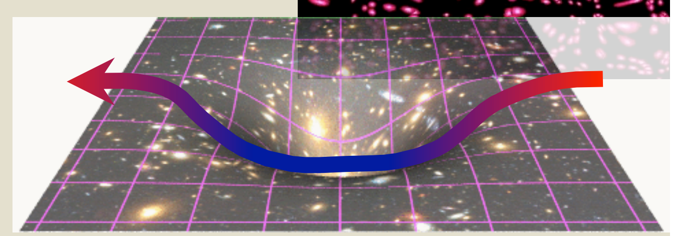
I: Background expansion	II: Growth, up to some normalization	III: Growth directly
CMB angular diameter distance	Galaxy autocorrelations	CMB ISW autocorrelation
Supernovae luminosity distance	Galaxy – ISW x-corrln	Weak lensing autocorrelation
BAO angular/radial scale	Xray and SZ galaxy cluster measurements	Peculiar velocity distribution/ bulk flows
	Ly-alpha measurements	











Phenomenological model of gravity

- Perturbed metric $ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2$
- Aim to describe phenomenological properties common to theories
  - A modification to Poisson's equation, Q

$$k^2\phi = -4\pi G Q a^2 \rho \Delta$$

Q≠1: can be mimicked by additional (dark sector?) clustering/matter

  - An inequality between Newton's potentials, R

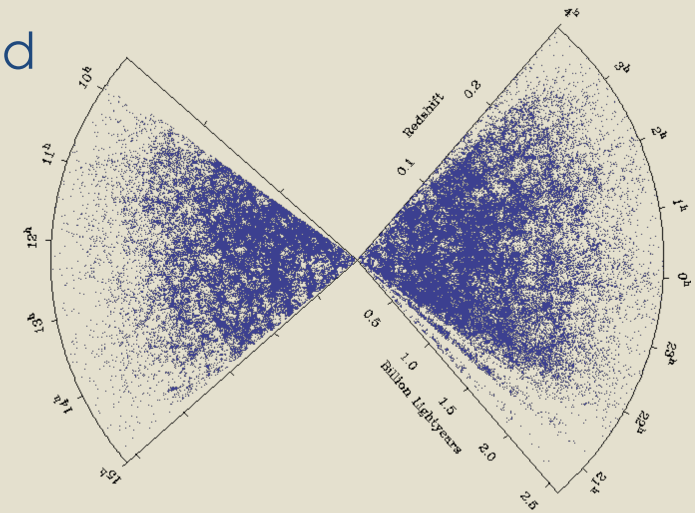
$$\psi = R\phi$$

R≠1: not easily mimicked.

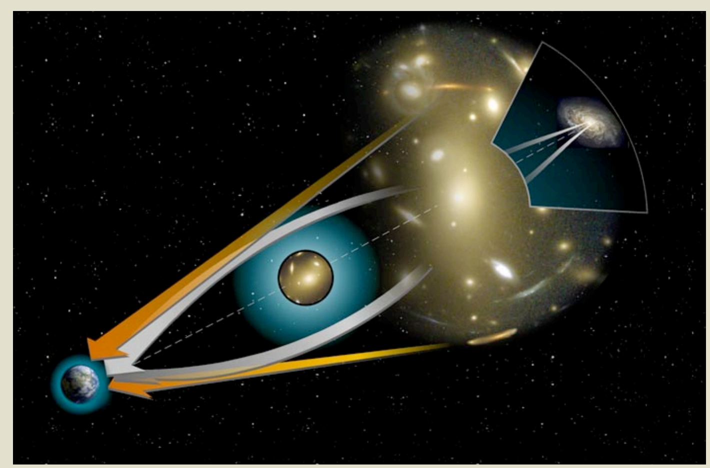
- potential smoking gun for modified gravity?
- Significant stresses exceptionally hard to create in non-relativistic fluids e.g. DM and dark energy.

Complementary tests of gravity

- Non-relativistic tracers: Galaxy positions and motions
  - Measure $\psi \sim G_{mat} = QRG_N$
  - Biasing of tracer (galaxy) issue



- Relativistic tracers: Weak lensing and CMB
  - Sensitive to $(\phi+\psi) \sim G_{light} = Q(1+R)G_N$
  - Direct tracer of potential, but still
    - stochasticity relating lensing and surveyed galaxies
    - plenty of systematics (photo-z, IAs…)



- Contrasting tracers are the key to understanding gravity

A "smoking gun" for GR on cosmic scales

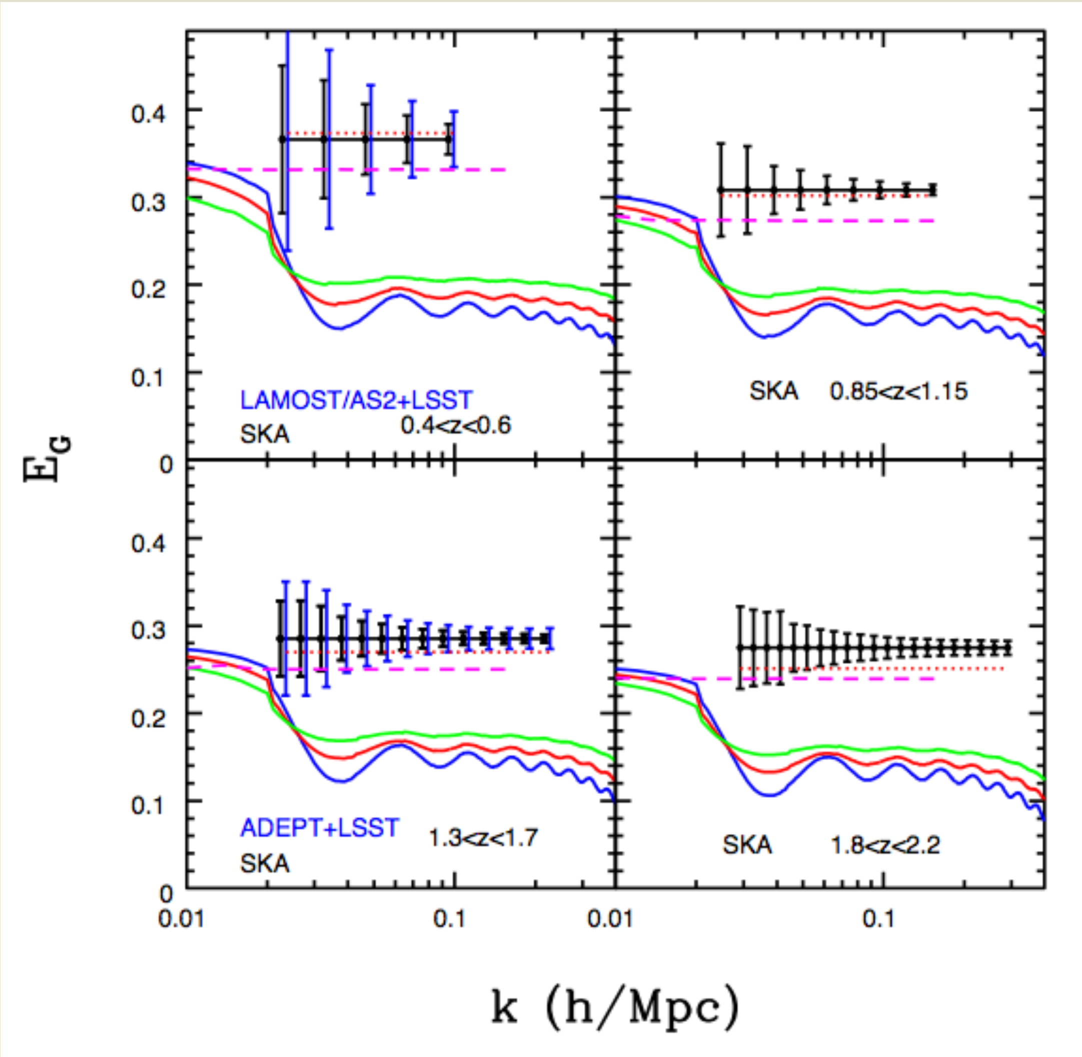
$$E_G \sim \frac{\text{galaxy position-lensing correlation } (C_l^{gG})}{\text{redshift space – galaxy position correlation } (C_l^{g\Theta})}$$

- Contrasts relativistic and non-relativistic tracers => $R \neq 1$?
  - Lensing: $G \sim \phi+\psi \sim Q(1+R)$,
  - Galaxy position and motion: $g,\Theta \sim \psi \sim QR$
- Independent of galaxy bias and initial conditions

$$\frac{C_l^{gG}}{C_l^{g\Theta}} \sim \frac{b\,\sigma_8^{\,2}}{b\,\sigma_8^{\,2}}$$

Zhang. Liguori, RB, Dodelson PRL 2007

Distinguishing between modified gravity and Λ

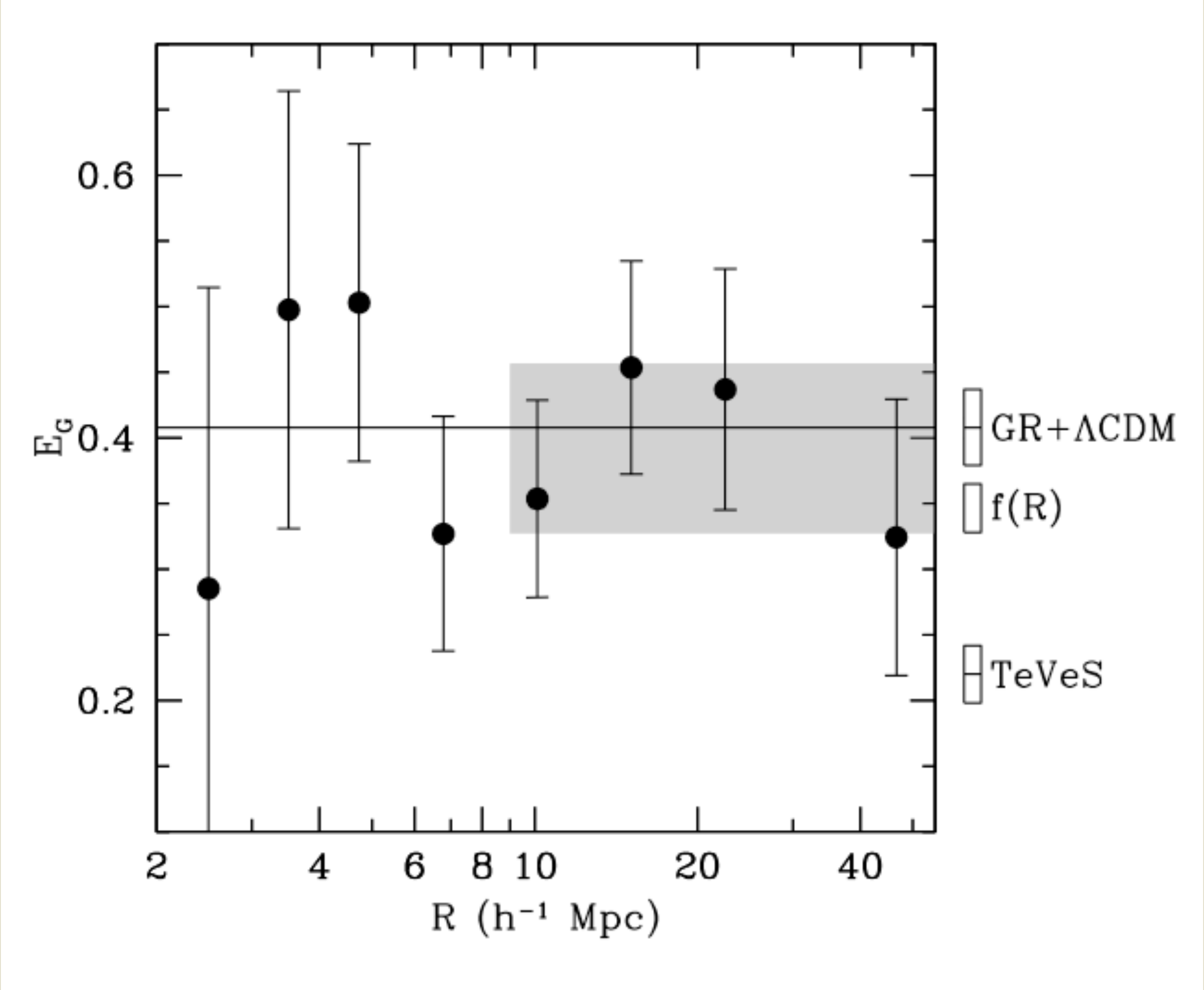


$$E_g \sim \frac{C_l^{g\kappa}}{C_l^{g\Theta}}$$

- GR
- DGP
- f(R)
- TeVeS K=0.1
- TeVeS K=0.09
- TeVeS K=0.08

Zhang, Liguori, RB, Dodelson PRL 2007

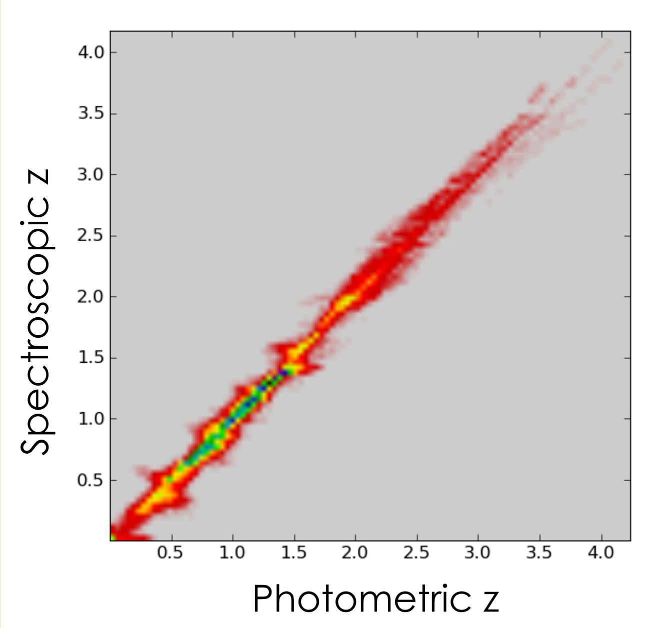
Vital proof of principle with SDSS LRG data



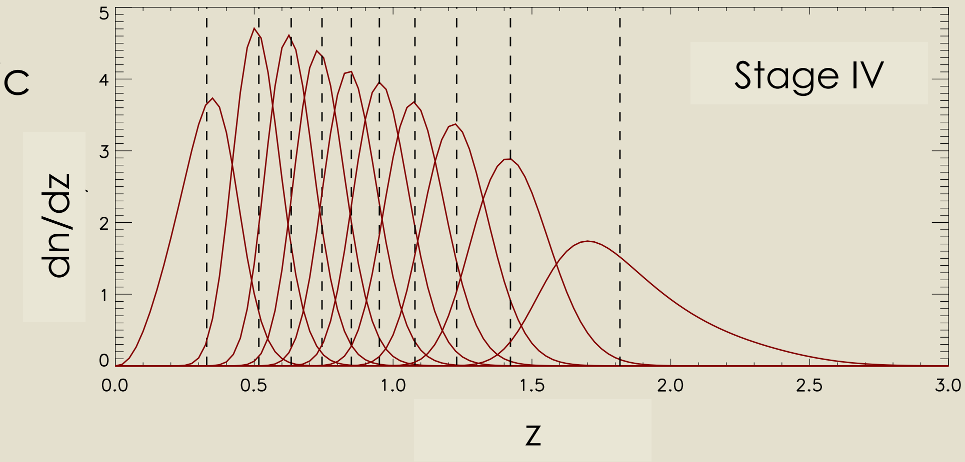
Reyes et al Nature 2010

Complications: photometric redshifts

- Facilitates fast and wide survey
- Enables tomography
  - Measuring evolution on dark energy
  - Cross-correlations between z bins useful for disentangling systematics and cosmology
- But sensitive to modeling
  - galaxy distribution,
  - photo-z statistical accuracy, systematic offsets and catastrophic errors



Credit: LSST Consortium



Complications : Intrinsic alignments

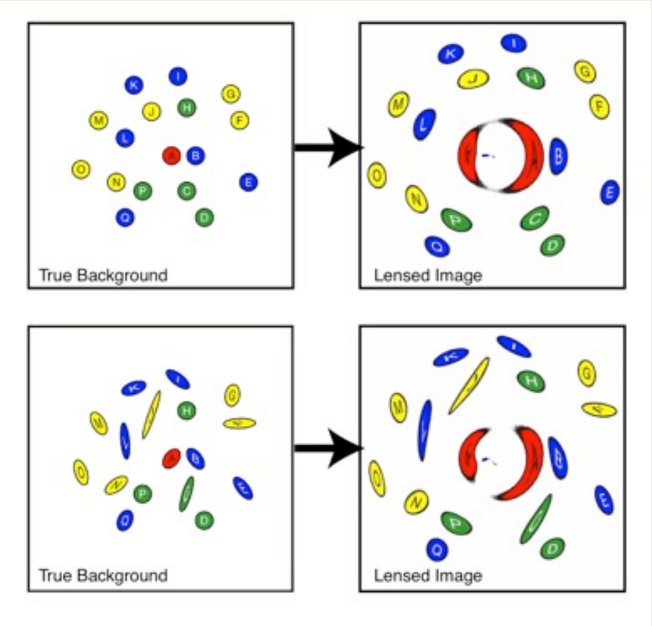
- Lensing distortions detected using statistical correlations

$$\epsilon^i(\theta) \quad = \quad \gamma^i_G(\theta) + \gamma^i_I(\theta) + \epsilon^i_{rnd}(\theta).$$

- Random ellipticity not an issue

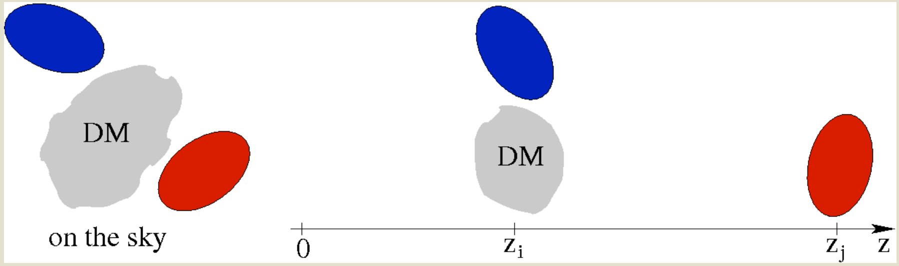
- Instrumental & astrophysical "contaminants" introduce systematic shear calibration uncertainties

- Correlated contaminantS need to be modeled and disentangled from cosmological shear
  - E.g. Intrinsic galactic alignments



Credit: Williamson, Oluseyi, Roe 2007

Cosmo+Intrinsic shear (anti) correlation

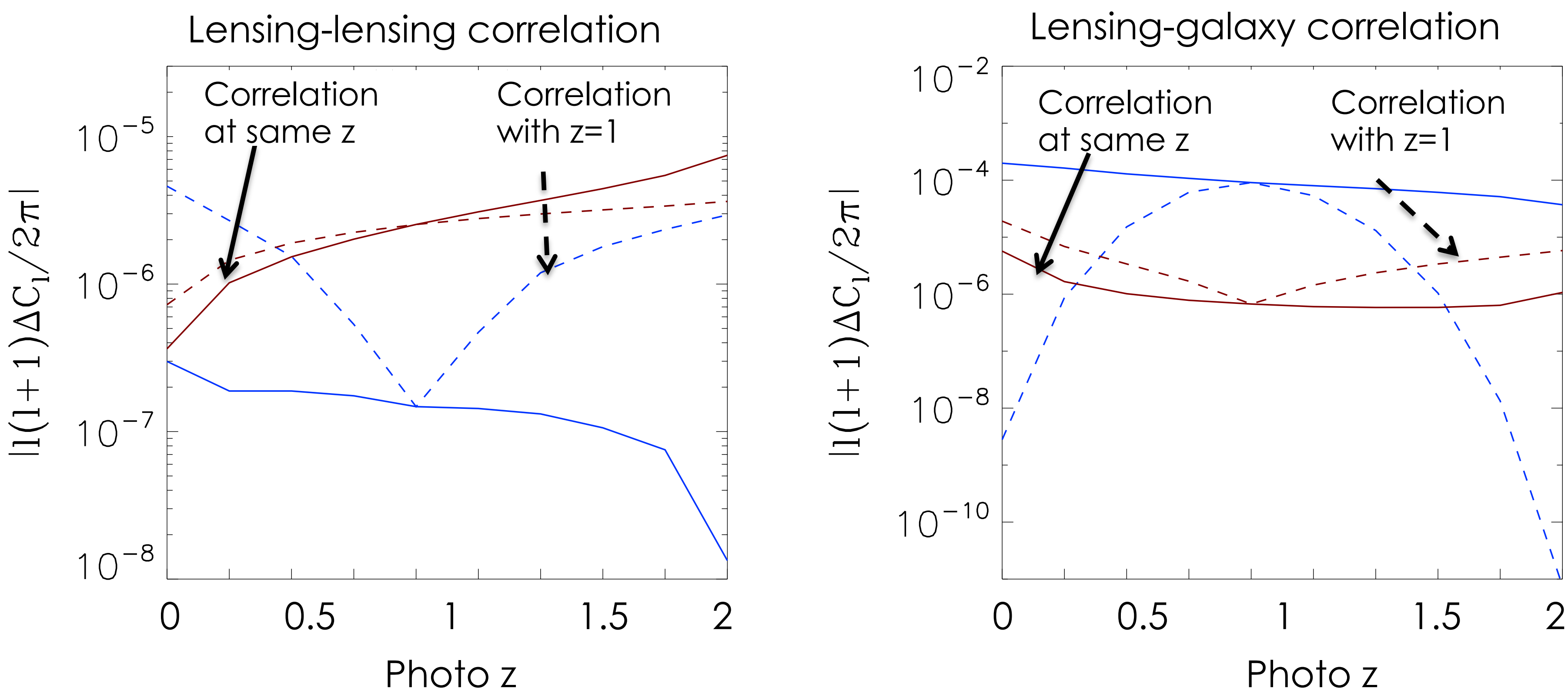


Credit: Benjamin Joachimi, iCosmo

Cross- correlations and tomography

- Use difference in redshift signatures to break degeneracy between systematics and dark energy theory

Differences between LCDM + sys errors vs no sys and MG vs LCDM for lensing and galaxy



Laszlo, Bean, Kirk, Bridle, MNRAS 2012

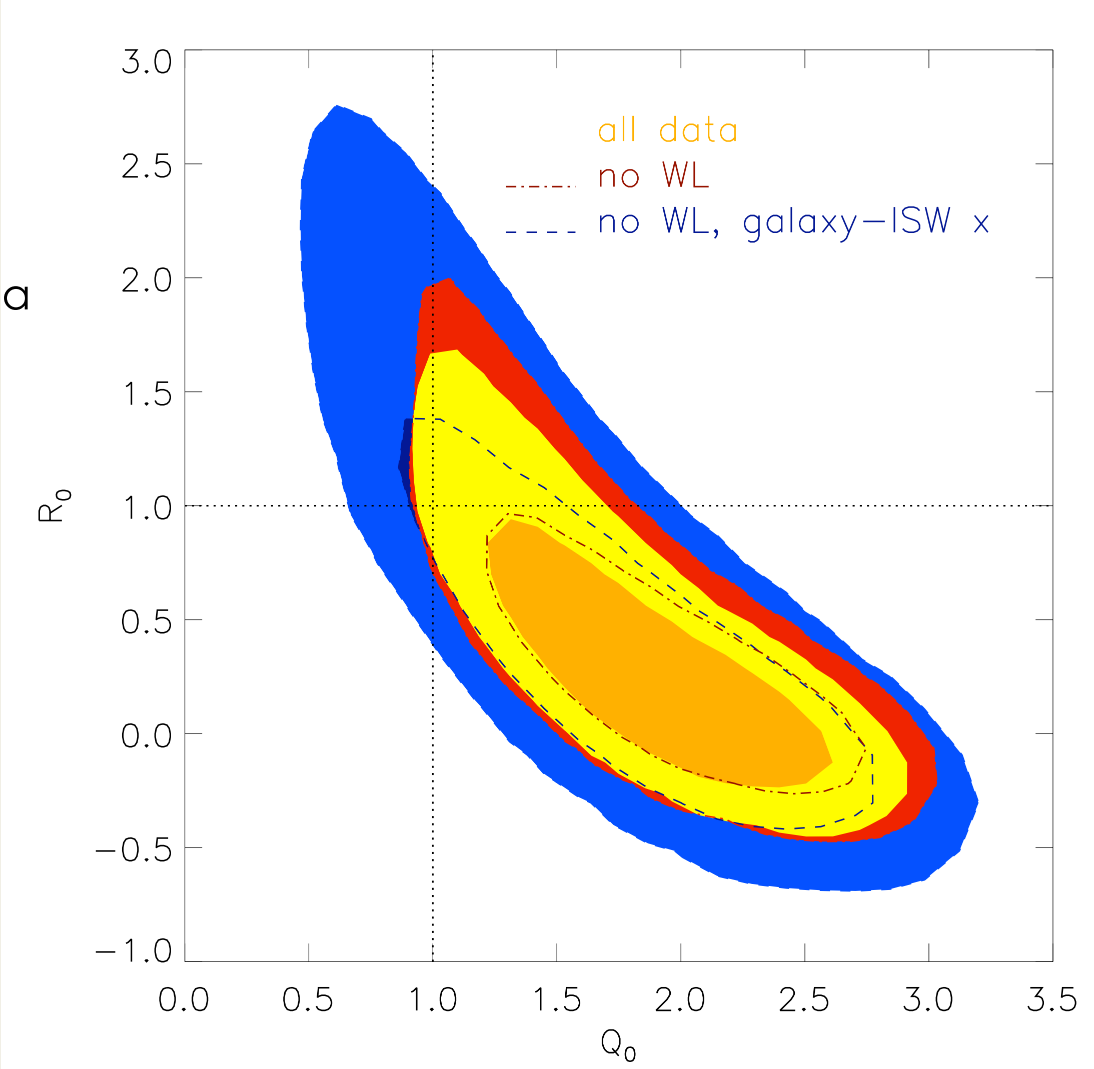
Current constraints

- Multiple data
  WMAP CMB, SDSS LRG auto ,
  SDSS-WMAP cross correlation,
  COSMOS weak lensing, Union SN1a

- CMB-galaxy correlations
  give best constraints

- Worst constraint from lensing +CMB
  - $(\phi+\psi)$direction ~Q(1+R)/2

- "Figure of Merit"
  - 1/error ellipse area
  - MG FoM ~ 0.03



Bean & Tangmatitham PRD 2010

What about future surveys?

- Fisher matrix analysis = Inverse covariance (error) matrix

$$Cov^{-1}_{ij} = F_{ij} = \frac{\partial t_a}{\partial p_i} Cov^{-1}_{ab} \frac{\partial t_b}{\partial p_j}$$

- Assumed cosmology and parameterization

$$\mathbf{p} = \{\Omega_b h^2, \Omega_m h^2, \Omega_k, \tau, w_0, w_a, Q_0, Q_0(1+R_0)/2, n_s, \Delta^2_{\mathcal{R}}(k_0), \\ +\text{systematic nuisance parameters}\}$$

- Datasets

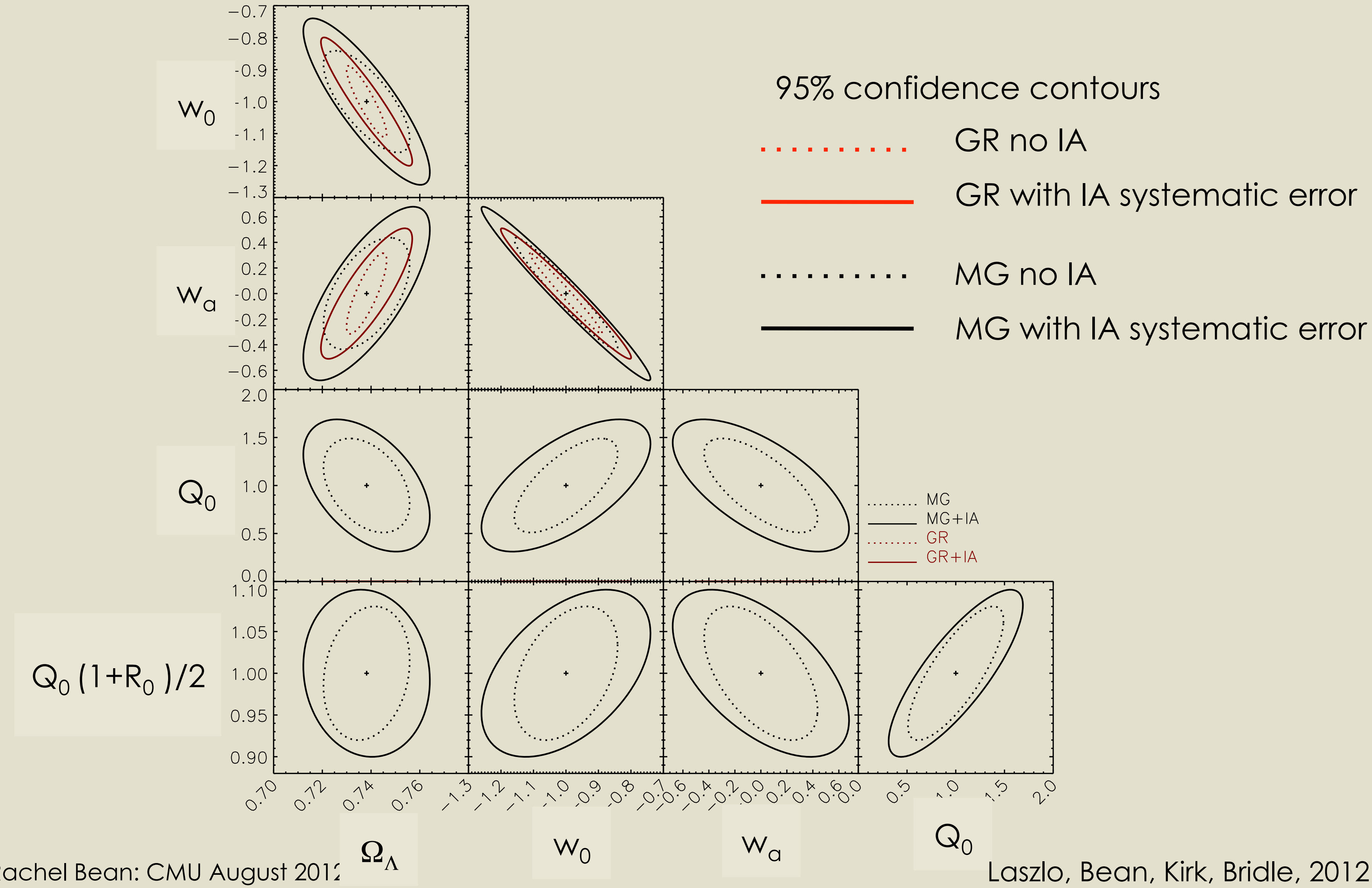
$$\mathbf{t} = \{C_\ell^{TT}, C_\ell^{TE}, C_\ell^{EE}, C_\ell^{Tg_1}, ..., C_\ell^{Eg_1}, ...C_\ell^{g_1 g_1}, C_\ell^{g_1 g_2}, ..., C_\ell^{\kappa_{N_{ph}} \kappa_{N_{ph}}}\}$$

- Survey specifications
  - near future (stage III) and end of decade (stage IV) surveys
  - Stage III = Planck CMB + DES-like imaging + BOSS spectroscopic surveys
  - Stage IV = Planck CMB + EUCLID-like imaging and spectroscopy

Forecasting: what you put in=what you get out

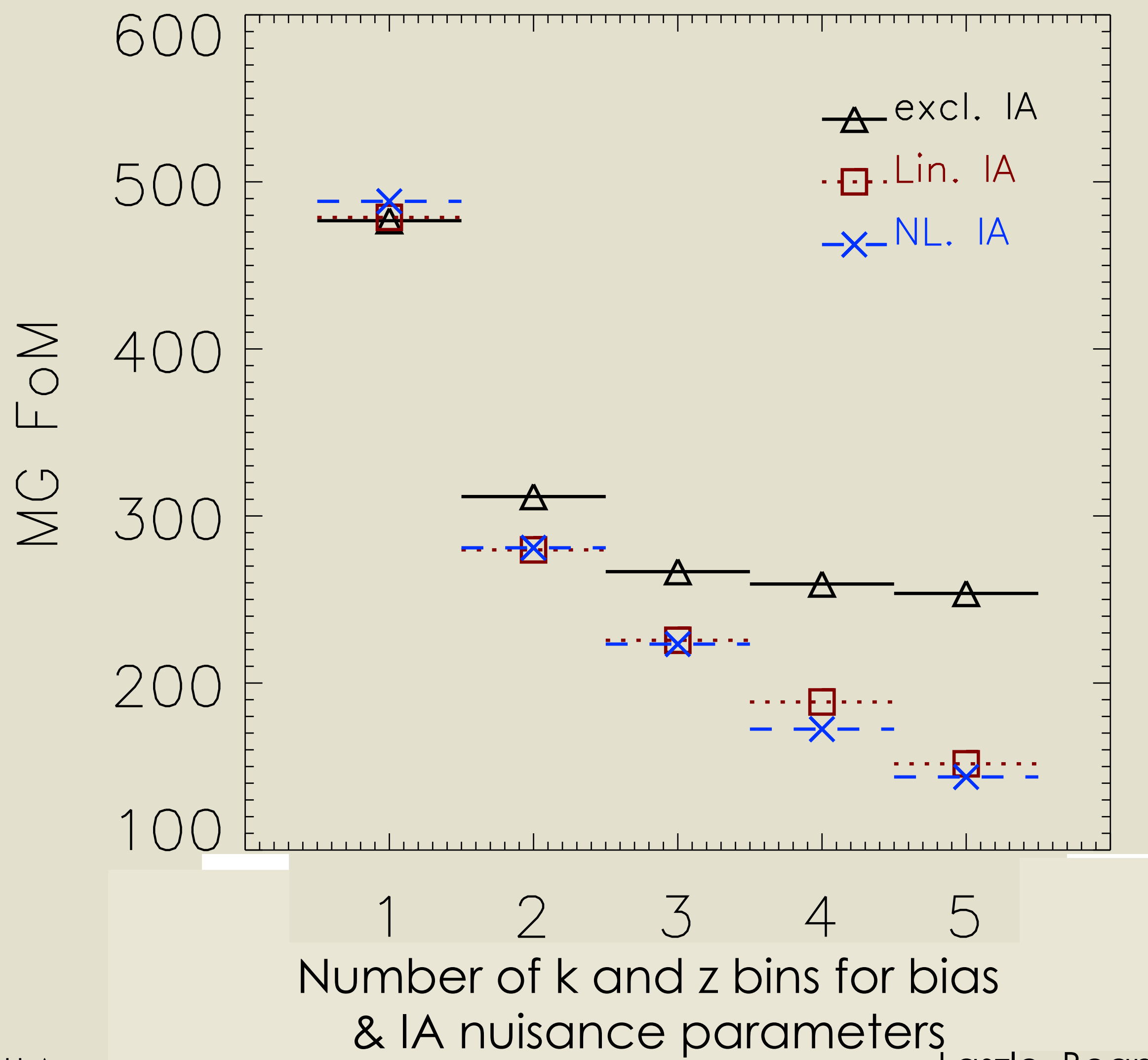
- Figures of merit /Fisher insightful but
- Model dependent – e.g. w0/wa or functions of z?
- Systematic errors difficult but important!
  - Instrumental e.g. calibration uncertainties
    - Internal cross-checks: inter-filter, concurrent & repetition ≠ redundancy
  - Modeling: e.g. Photo z modeling errors, nonlinearity
    - Access to ground based facilities,
    - Training sets, simulation suites
  - Astrophysical: e.g. IAs , Hα z distribution, galaxy bias, baryonic effects
    - At what scale should one truncate the analysis?
    - Analytical modeling, gridded k& z bins, simulations?
- Buyer beware!
  - risky to compare FoM unless apples-for-apples treatment

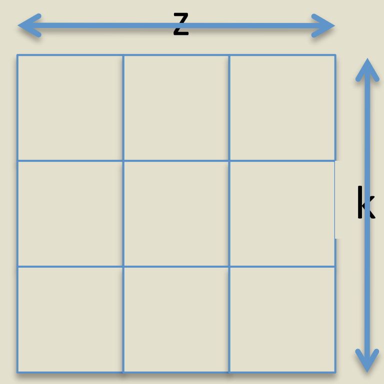
Sensitivity to theory and systematics



Laszlo, Bean, Kirk, Bridle, 2012

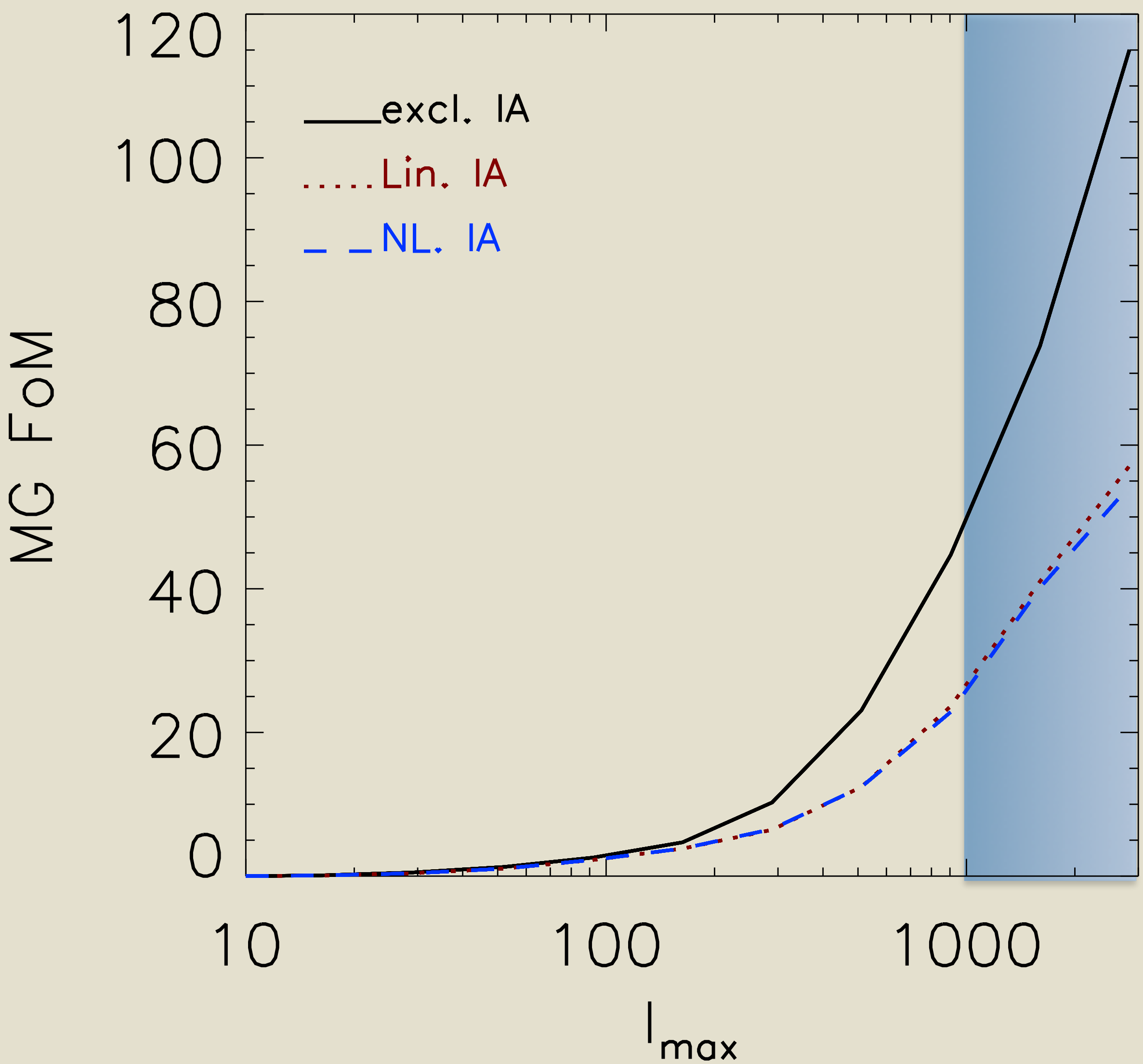
Our level of understanding about bias and IA is important





Laszlo, Bean, Kirk, Bridle, MNRAS 2012

If you understand non-linear scales they could make a big difference



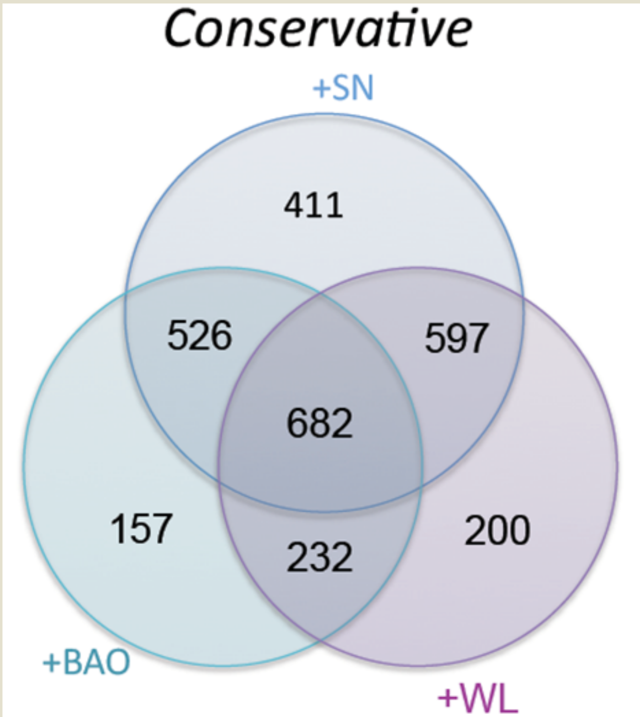
On scales <~ a few Mpc

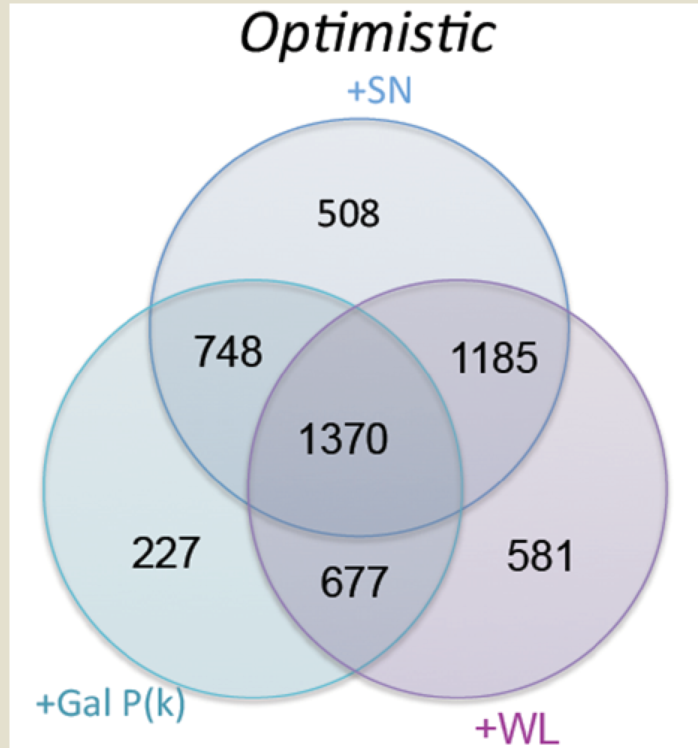
- Baryonic effects?
- Non-linear modeling?
- Screening effects?

Include small scale modeling uncertainties in forecasts.

Laszlo, Bean, Kirk, Bridle, MNRAS 2012

WFIRST design prioritizes systematic control





Chris Hirata's talk

WFIRST SDT final report 1208.4012

Concluding thoughts

- Invaluable opportunity to test the origins of cosmic acceleration and weak field gravity on cosmic scales
  - Theoretical developments, fast evolving.
  - General effective field theory for DE a useful phenomenological approach,
  - interesting implications for both expansion history and growth history
- Multiple, complementary astrophysical tracers key to finding DE origin
  - geometric techniques important record of expansion history
  - relativistic & non-relativistic LSS tracers sensitive to gravity's properties
  - Surveys will give us information across z and from horizon to sub-halo scales
- Honest assessment of systematics essential
  - Theory and systematics can be tightly coupled.
  - Can significantly impact predictions (beware apples vs oranges)
  - Survey and algorithm development + x-corr important to mitigate these.
- FoMs useful but a high pass filter on data. Mapping to the underlying theory is the ultimate goal.